THE ASTROPHYSICAL JOURNAL, 164:111–114, 1971 February 15

LITHIUM AND THE *s*-PROCESS IN RED-GIANT STARS

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Received 1970 July 23

ABSTRACT

Some consequences are discussed of the possibility that helium-burning shell flashes in advanced stages of stellar evolution occasionally induce complete convection of the outer envelope down to the helium-burning shell. If the hydrogen mixing is relatively small for the first 10^7 seconds, the result may be the production of large amounts of heavy elements by the *s*-process. When complete mixing commences, the ^{3}He in the envelope will be converted to ^{7}Be, and the subsequent delayed electron capture to form ^{7}Li may allow enough lithium to remain near the surface to account for the very large lithium abundances in some S and carbon red-giant stars. On this basis the ^{7}Li/^{6}Li ratio in these stars should be quite large (>100).

I. INTRODUCTION

The lithium content of red-giant stars is highly variable (Wallerstein and Conti 1969). The largest amounts of lithium are found in three carbon stars, WZ Cas, WX Cyg, and T Ara, being of the order of 10^{-2} of calcium. More recently Boesgaard (1970) has found a similar high lithium abundance in the S star T Sgr. This is a higher ratio of lithium to calcium than is found in T Tauri stars or in meteorites. It is therefore tempting to believe that the lithium has been produced by some internal process. However, since the majority of carbon and S giants do not possess nearly so much lithium, it is necessary to postulate that the production process involves some unusual events.

One of us (Cameron 1955) has suggested a possible mechanism for the internal thermonuclear production of lithium. Suppose that the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction takes place in the deeper interior of a star and that there is then outward convection of the gases to a place where the temperature is much cooler. The reaction $^7\mathrm{Be}(e^-\nu)^7\mathrm{Li}$, which requires the capture of one of the bound or continuum electrons, could then produce lithium under conditions where the lithium is not rapidly destroyed by thermonuclear reactions. If the first reaction is to proceed on a time scale comparable to or less than the stellar lifetime, the ^{7}Be production must take place at 10^7 ° K or higher. In order to preserve the ^{7}Li for an appreciable part of a stellar lifetime, it must be made and preserved in a region with a temperature of less than 3×10^6 ° K (Fowler, Caughlan, and Zimmerman 1967).

Parker, Bahcall, and Fowler (1964) have shown that the highest ratio of ^{7}Li/H that can be reached in the normal equilibrium operation of the proton-proton chains is 10^{-10}, which is two orders of magnitude smaller than would be needed to produce the large amounts of lithium in the giant stars mentioned above. Wallerstein and Conti (1969) have quoted this as evidence that the above mechanism would be inadequate to produce the required lithium, and Boesgaard (1970) similarly rejects the mechanism. However, there may exist some nonequilibrium situations where these considerations do not apply. In this note we discuss one such possible situation.

II. HELIUM-BURNING SHELL FLASHES

The later stages of stellar evolution are still most imperfectly understood. However, we believe that the mechanism of lithium production may have an opportunity to operate at the stage of the helium shell flashes, which occur at a late stage in evolution when a star has exhausted its central helium and obtains energy from hydrogen- and helium-burning shells (Schwarzschild and Härm 1965, 1967; Weigert 1966; Rose 1966, 1967). These investigators showed that the appearance of a thermal instability in the helium shell, resulting in a thermal runaway, or flash, caused the appearance of a convection zone extending from about the middle of the burning shell outward well into the surrounding nonburning helium layers. The calculations of Weigert referred to a star of 5 $M_{\odot}$, whereas the other calculations were for stars of about 1 $M_{\odot}$. Thus it appears that the phenomenon should be a general one which occurs in a wide range of stellar masses.

In the calculations of Schwarzschild and Härm (1967), the convection zone enriches the helium layer in carbon, and after nine relaxation cycles the helium flashes produce a convection zone extensive enough to reach into the hydrogen-burning shell and to mix some hydrogen into the deeper interior. The maximum penetration into the hydrogen layer occurred on the twelfth cycle; the thirteenth cycle did not penetrate as far. Still further computations indicated that the penetration diminished and eventually ceased in the later cycles (Schwarzschild, private communication).

The processes that may occur following the mixing of hydrogen into the helium layer have been analyzed in some detail by Sanders (1967). Some of the relevant features are the following. The helium zone contains about 7 percent of the stellar mass, and the material in this zone has only changed by 10–20 percent from one cycle to the next. About half of the material by mass in the zone consists of helium-burning products, of which a substantial fraction is ^{12}C. The period in which the convection zone extends into the hydrogen layer is of the order of 10^7 seconds, and the convective motions mix matter throughout the entire convective region in a matter of hours.

Sanders showed that the number of protons mixed into the helium layer in any one flash would release not more than 10 percent of the energy in the helium flash itself, in the maximum penetration cycle of Schwarzschild and Härm. Therefore he concluded that only minor effects on the structure and evolution of the star would occur.

One of the principal objectives of Sanders's paper was to examine the amount of *s*-process nucleosynthesis that could occur associated with the helium shell flashes. He correctly concluded that significant buildup of heavy elements could occur only in a Population II star of very low metal content. His actual numbers require some revision, since they were evidently based on the old solar photospheric iron abundance, which was too low due to incorrect oscillator strengths. Seven percent of a normal solar mass contains nearly 2×10^{51} iron atoms. The total number of admixed protons is of the order of 4×10^{50}. Almost all of these are converted to neutrons by the $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}$ and $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reactions. Since significant synthesis of heavy elements requires the production of 10–10^2 neutrons per iron nucleus (Clayton *et al.* 1961; Seeger, Fowler, and Clayton 1965; Seeger and Fowler 1966), it may be seen that significant *s*-process production of heavy elements would occur only if the metal content of the star is less than solar by two orders of magnitude.

III. MORE EXTENSIVE MIXING

The above detailed results refer only to a star of 1 $M_{\odot}$. Schwarzschild and Härm indicate that some uncertainty attaches to their calculated amounts of admixed hydrogen. Furthermore, the S and carbon red-giant stars under consideration in the lithium discussion are probably significantly more massive than the Sun. Weigert (1966) found that the convection zone following the helium shell flash in a 5 $M_{\odot}$ star also progressively approached the hydrogen layer, but the calculations were not continued long enough to determine whether penetration would occur. Thus we feel it is legitimate to ask what would happen if the number of admixed protons should become much larger than the Schwarzschild-Härm value in some range of stellar mass.

If half of the mass has been converted to ^{12}C in the helium layer, as in the Schwarzschild-Härm calculations, there would be about 3×10^{54} ^{12}C nuclei in the layer. Suppose that the number of admixed protons entering the layer were increased by three or four orders of magnitude to the range 0.1–1 proton per ^{12}C nucleus, under conditions in which the ^{13}C, formed by proton capture in ^{12}C, is cycled many times to higher temperatures. Then the ^{13}C would be continually destroyed by helium burning, most of the protons would still be converted to neutrons, and hence more than 10^4 neutrons per iron nucleus would be produced in material of stellar Population I composition. However, the resulting additional energy release would already greatly exceed that of the original helium flash when two orders of magnitude more protons had been mixed inward, probably leading to structural changes when about ten neutrons per iron nucleus had been produced. This range of neutron production is precisely what is needed for the operation of the *s*-process in nature.

The great strength of this neutron source is certainly encouraging, but a few cautionary words are needed regarding the time scale. The *s*-process must take place relatively *slowly*, at least during the capture of the last few neutrons in any major source. The Schwarzschild-Härm calculations indicate a time scale of 10^7 seconds for the protons to mix inward in any one helium shell flash. A similar time scale would be required in the present considerations before the accumulated energy release initiated major structural changes. The key to this is the β-decay half-lives of the products of neutron capture on the *s*-process nuclides. In most cases these lie in the range hours to days, if accelerated decays through Boltzmann-populated excited states are taken into account; but in some cases the half-lives are a few months. Thus 10^7 seconds seems to be a minimum acceptable time for the operation of the *s*-process, in order to avoid the production by the *s*-process of too much of the neutron-rich isobars normally assigned to the *r*-process, and the depletion of the corresponding *s*-process isobars.

The major structural change initiated by the extra energy release of the admixed protons presumably consists of the outward extension of the convection zone of the helium layer, until it joins the deep outer convection zone that extends downward from the surface of a red-giant star. Thereafter, for a time, the entire envelope of the star may be mixed down to a temperature of 10^8 ° K. This would certainly bring the *s*-process products to the surface and enrich the carbon content of the outer layers, changing the spectrum to that of a carbon or S red-giant star. The dilution of the helium layer by large amounts of hydrogen would effectively terminate the *s*-process, partly by diluting the *s*-process products with additional iron, but mainly by introducing large amounts of neutron poisons such as ^{14}N and the protons themselves. Such an extensive mixing process, if it occurs, would also be of interest for the lithium problem.

In an extensive series of papers dealing with the advanced stages of evolution of stars covering a wide range of masses, Iben (1965, 1966*a*, *b*, *c*, 1967*a*, *b*) has shown that ^{3}He builds up to quite large abundances some distance beyond the hydrogen-burning shells. His maximum values of the ^{3}He abundance by mass lie in the range 10^{-6} to 10^{-2}, with the smaller values being more characteristic of larger masses and later stages in the evolution. The half-width of his ^{3}He distributions is typically about 20 percent of the stellar mass.

We now suppose that the hydrogen envelope is mixed down to a temperature of 10^8 ° K, with the local mixing time near the base of the convecting region being a few hours as it was in the Schwarzschild-Härm calculations. The lifetime of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction is a few hours near 8×10^7 ° K. It is thus evident that the ^{3}He content of the stellar envelope would be converted to ^{7}Be. Even if the *average* ^{3}He mass fraction in the outer envelope is only 10^{-7}, the amount of ^{7}Be produced would be a factor of 10 higher than the lithium abundances in WZ Cas, WX Cyg, T Ara, and T Sgr. Most of the ^{7}Be would be mixed to a much cooler region before the formation of ^{7}Li by electron capture takes place. It would seem possible that much of the ^{7}Li could be preserved at the surface once the outer envelope has relaxed back toward its former state.

IV. DISCUSSION

The above picture of a fully convecting but temporary stellar envelope with a base temperature of 10^8 ° K is a concept which is far from justified by astrophysical calculations performed to date. The nuclear consequences of this picture are very interesting, and deserve to be worked out in more detail. They suggest that this mechanism, in its early stages, could be responsible for the *s*-process production of heavy elements in red-giant stars. If this is so, this may be the major source of *s*-process nuclides in nature, owing to the extensive mass loss from the envelopes of red-giant stars. Potentially very large amounts of lithium may be produced by the ^{7}Be transport mechanism of Cameron (1955).

It is evident that this is an area of interaction between stellar-evolution theory and nucleosynthesis which should be more fully explored.

This research has been supported in part by National Science Foundation grant GP-14527, National Aeronautics and Space Administration grant NGL-33-023-018, and the Office of Naval Research [Nonr-220(47)].

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